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Increasing cities' capacity to manage noise and air quality using urban morphology

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Abstract

According to the World Health Organization, the top two in disease burden are air pollution and environmental noise. In cities, road traffic is the largest contributor to both noise and air pollution and the corresponding Swedish Environmental objectives are to date estimated to not be reached by 2020. Future reductions concerning both air quality and noise are considered insufficient whereby additional measures are needed.

Air quality is linked to urban form such that compact cities were shown to result in increasing concentrations of air pollution. Further, urban form influences the meteorology due to changed surface roughness on the larger scale (urban scale), and even more in a local- and microscale at ground level in street canyons. This will affect wind patterns influencing the dispersion possibility of air pollutants.

For investigating local effects of urban morphology on noise and air distribution simultaneously, the Spacematrix method has been shown to be useful, as described in Berghauser Pont and Haupt (2010). Building types can be composed of a combination of density variables enabling to quantify a type and manipulate each variable separately. The aim of this paper is to identify critical spatial parameters influencing noise and air pollution and translate them into measures of spatial form including size of the urban block, and distribution, positioning and height of the buildings within that block.

Introduction

According to the World Health Organization, the top two in disease burden among environmental factors in Europe, are air and noise pollution (WHO 2018, 2019). Numerous studies, both international and Swedish, have shown that air pollution, especially particles, contributes to long term morbidity and mortality from cardiovascular and respiratory diseases (Brook et al. 2012; Zang et al. 2014; Fridell et al. 2014). Concerning noise, there is significant and increasing evidence for serious health effects due to long-term exposure of high-level traffic noise in dwellings, including annoyance, sleep disturbance and ischaemic heart disease (Basner et al. 2013; Munzel et al. 2014). Also, combinations of noise and air pollution health effects have been studied (e.g. Tonne et al. 2016; Stansfield 2015).

Road traffic is the largest contributor to both noise and air pollution in cities (e.g. nitrogen oxide and particles as PM10). Furthermore, the overall trend is negative (Swedish Environmental Objectives, 2019). Future reductions at source are considered insufficient whereby additional measures are needed. This paper focuses on additional measures by identifying the role of critical spatial parameters influencing noise and air pollution. Further, until today, noise and air pollution has mostly been treated separately, which is ineffective with respect to production of new housing areas and may lead to unnecessarily bad living environments. Therefore, in this paper, the impact of these spatial parameters on noise and air pollution will be assessed jointly.

Urban morphology, more specifically the form and placement of buildings in relation to roads, will be used to frame and measure the spatial parameters to then test how these can reduce both noise and air pollution. A simplified example is a courtyard with an opening toward a busy street that facilitates ventilation of the street space and thereby improves the air quality in the street. Simultaneously, the noise transmission through such an opening deteriorates the sound environment and may hinder the quiet side requirement to be attained in the courtyard.

The aim of the paper is to systematically test the role of a set of critical spatial parameters on the distribution of noise and air pollution. In what follows, we will first give an overview of what is already known about this impact. Then, the methodology for the analysis will be described, the theoretical urban models to test the relation will be introduced and the results presented. In the final section, we summarise the conclusions and discuss directions for future research.

Background

Compact cities have been shown to result in higher concentrations of air pollution than dispersed ones (Borrego et al. 2006; Martins 2012). Further, urban form influences the meteorology due to changed surface roughness, affecting wind on an urban scale (Kwak et al. 2015), which in turn influences the transport of air pollutants as well as noise propagation to longer ranges. In smaller scale, blocks with similar roof top heights cause a more laminar wind flow contrary to individual high houses (Haeger-Eugensson et al. 1999). Initial studies show that air pollution levels may either decrease or increase, at least locally, due to urban geometry (Garcia et al. 2103).

Concerning courtyard openings toward roads, they may reduce air pollution concentrations due to the created wind ventilation (Haeger-Eugensson et al. 2013). Such openings may however prevent an effective reduction of noise levels in the courtyard (e.g. Hornikx et al. 2011). This so-called ‘quiet side concept’ is something urban densification projects rely to a large extent on, i.e. allowing higher noise levels toward the noisy street if a quiet (or damped) side to each apartment is guaranteed (e.g. City of Gothenburg 2016).

To investigate local effects of urban morphology on noise and air distribution, the Spacematrix method has been shown useful, as described in (Berghauser Pont and Haupt 2010) and tested for daylight performance (ibid) and noise pollution (Salomons and Berghauser Pont 2012). Berghauser Pont and Haupt (2010) developed a multi-variable method to measure built density including four variables that are all well-known variables in urban development practice: floor space index (FSI), expressing the intensity of the built environment; ground space index (GSI), describing the compactness of an urban block or area, that is, the coverage of the area with buildings; building height that is self-explanatory; and open space ratio (OSR), also referred to as spaciousness, an indicator of the intensity of the use of unbuilt space. It is shown that various morphological types can be distinguished numerically by expressing density through this composite of variables (Berghauser Pont and Haupt, 2010). Each spatial solution, high and spacious or low and compact, results in a unique combination of the density variables and thus has a unique position in the Spacemateⁱ diagram (Figure 1). This method allows us to study the effects of building type (such as closed perimeter blocks, point and slab buildings) on the distribution of noise and air pollution, while at the same time controlling for the different density variables. In other words, we will answer question such as: Are closed perimeter building blocks a better solution than point buildings with the same floor space index (FSI) when noise and/or air pollution are considered?; Does this performance change when we keep the variable building height constant instead of FSI? In an earlier study on daylight performance using daylight simulation software, it was found that the daylight performance gradients are comparable to the OSR gradients (Berghauser Pont and Haupt, 2010). We will therefore follow the same methodology, but now applied on air and noise pollution.

Methodology

To test the relation between the Spacemate variables and noise and air pollutions, firstly, six theoretical urban models (cases) are developed that will be discussed in detail belowⁱⁱ. Secondly, we use simulation software to calculate the levels of noise exposure and air

pollution in space. Thirdly, the relation between urban form and noise exposure and air pollution are studied. These three steps will be discussed in more detail below.

Urban models based on the Spacematrix methodology

Berghauser Pont and Haupt (2010) showed that a multivariable density concept consisting of three density variables offers a method to define building types, which these variables separately were incapable of doing. The variables used are well-known indicators of density where ground space index (GSI) describes the use of the ground in two dimensions and floor space index (FSI)ⁱⁱⁱ describes the intensity of the use of the ground floor by stacking floor space in the third dimension. The equations added here.

$$GSI_x = B_x/A_x \quad \text{equation 1}$$

where

B = footprint (m²)

A = area of site (m²)

x = scale level (e.g. parcel/lot, urban block/island, neighbourhood)

$$FSI_x = F_x/A_x \quad \text{equation 2}$$

where

F = gross floor area (m²)

A = area of site (m²)

x = scale level (e.g. parcel/lot, urban block/island, neighbourhood)

Based on FSI and GSI, a third variable can be derived: the average height (i.e. amount of floors) of the buildings (L), using the following equation:

$$L_x = FSI_x/GSI_x \quad \text{equation 3}$$

Another variable that can be derived from FSI and GSI is spaciousness (also called open space ratio, OSR) and provides an indication of the intensity of use of the non-built space, calculated with the following equations:

$$OSR_x = (1-GSI_x)/FSI_x \quad \text{equation 4}$$

All four variables can be represented simultaneously in a scatter graph named Spacemate with FSI on the y-axis and GSI on the x-axis; OSR and L are gradients that fan out over the diagram. By plotting a large number of observations (i.e. neighbourhoods) on the Spacemate, Berghauser Pont and Haupt (ibid.) showed convincingly that building types cluster. High-rise strip types and mid-rise block types with similar FSI position at distinct location on the graph due to differences in GSI, OSR and L (Figure 1).

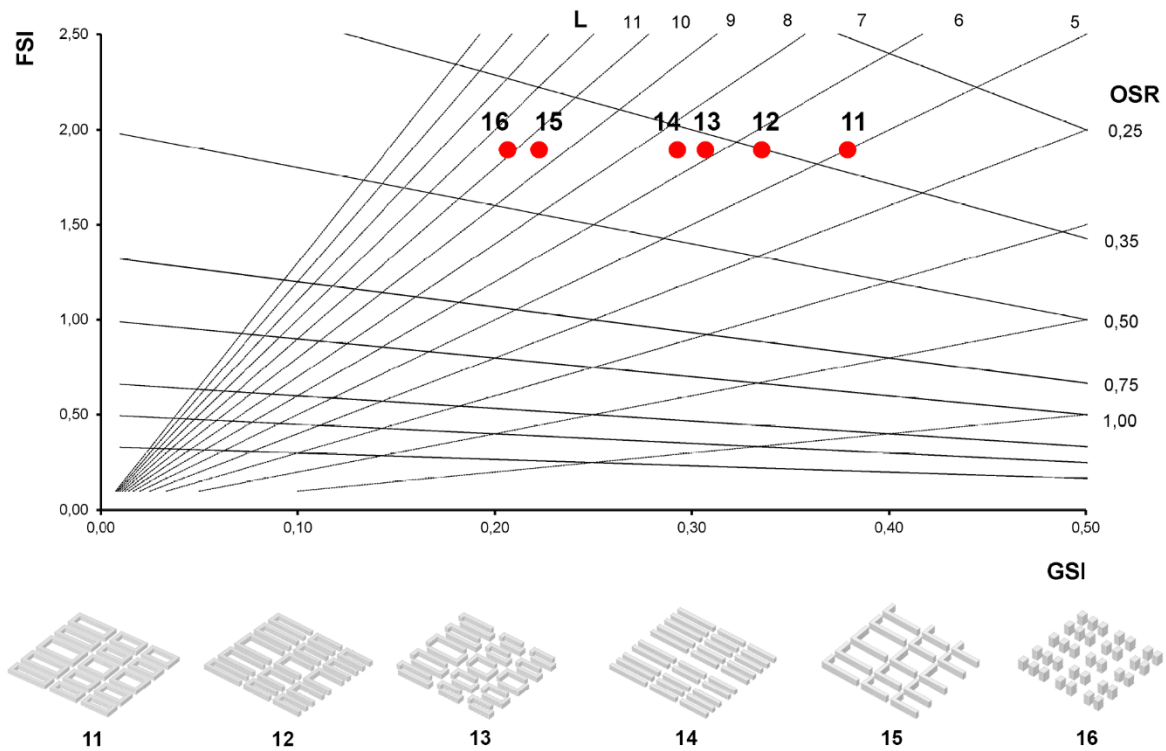


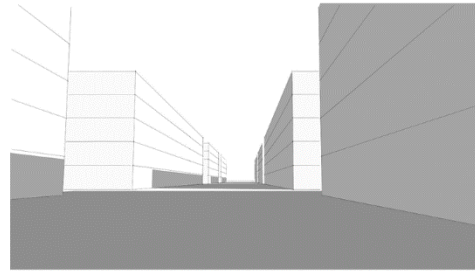
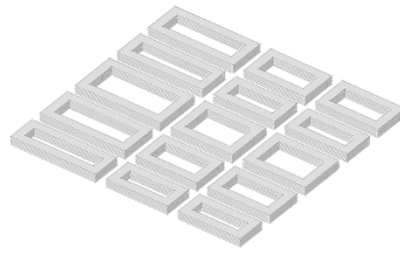
Figure 1. Spacemate diagram with the six building types.

To study the effects of building types on the distribution of noise exposure and air pollution, we developed theoretical cases based on six different building types, located in an unbuilt area in central Gothenburg. The location is needed to have a constant, but realistic background level of noise exposure and air pollution, where we then place the six cases to study the isolated effect of changes in building type and density, using the Spacematrix method.

The theoretical cases are the three archetypical types closed perimeter building blocks (case 11), slab buildings (case 14) and point buildings (case 16) and three in-between types where the closed building block is opened on one side (U-block, case 12), on two sides (L_block, case 15) and lastly, on two opposite corners (case 13). From earlier empirical studies (Berghauser Pont and Haupt, 2010), we know that these types are found in different positions in the Spacemate diagram where the closed building block (case 11) has the highest GSI and the point building (case 16) the lowest GSI (Figure 1 and 2).

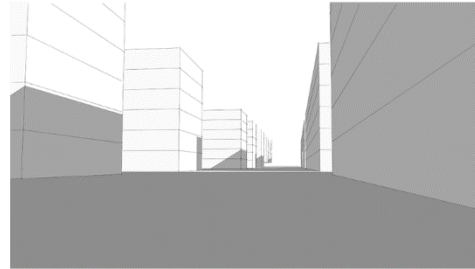
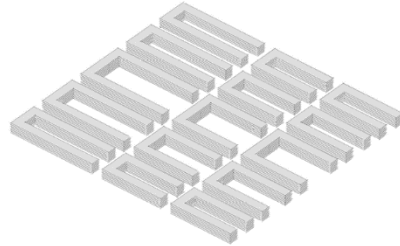
Case 11

FSI 1,82
GSI 0,36
OSR 0,35
L 5,0



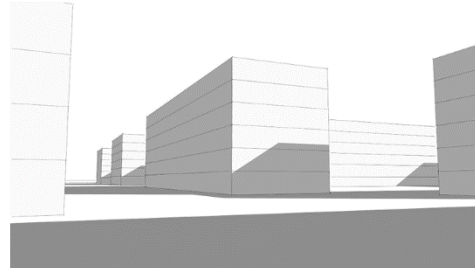
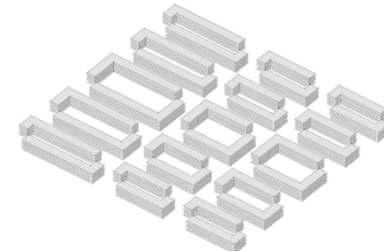
Case 12

FSI 1,82
GSI 0,33
OSR 0,37
L 5,6



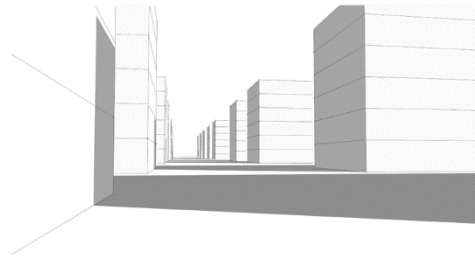
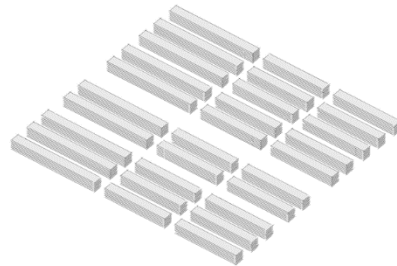
Case 13

FSI 1,82
GSI 0,29
OSR 0,39
L 6,4



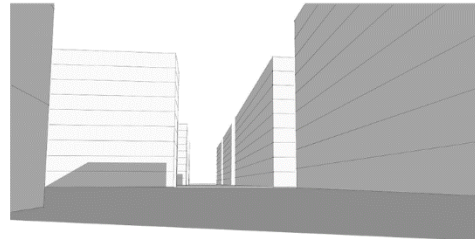
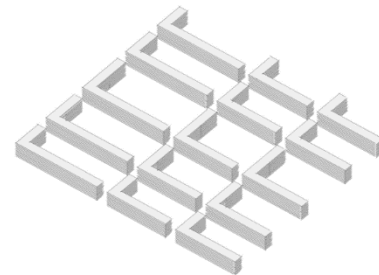
Case 14

FSI 1,82
GSI 0,29
OSR 0,39
L 6,4



Case 15

FSI 1,82
GSI 0,20
OSR 0,44
L 9,1



Case 16

FSI 1,82
GSI 0,13
OSR 0,48
L 14,0

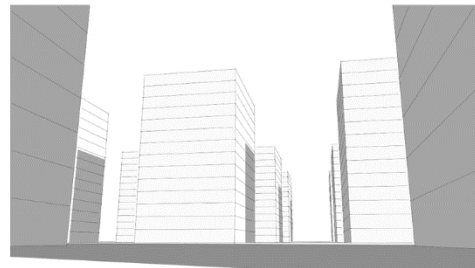
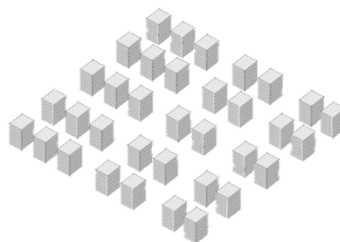


Figure 2. Theoretical cases tested in this paper.

To study the effect of urban form and density on air and noise pollution, we tested this series of building types, keeping FSI constant. The building height thus varies and for the closed building blocks (case 11), the height is set to five floors. When GSI decreases and FSI is constant, the building height must increase from five storeys in case 11 to 14 floors in case 16, the point buildings (Table 1).

ID	Type	Area	Footprint	GFA	Spacematrix			
					FSI	GSI	Floors	OSR
		m ²	m ²	m ²	GFA/Area	B/Area	FSI/GSI	(1-GSI)/FSI
11	block	201 535	73 482	367 410	1,82	0,36	5,0	0,35
12	U-block	201 535	65 532	367 410	1,82	0,33	5,6	0,37
13	open corners	201 535	57 634	367 410	1,82	0,29	6,4	0,39
14	strip	201 535	57 510	367 410	1,82	0,29	6,4	0,39
15	L-block	201 535	40 158	367 410	1,82	0,20	9,1	0,44
16	point	201 535	26 250	367 410	1,82	0,13	14,0	0,48

Table 1. Density values of the theoretical models (cases) tested in this paper.

Modeling noise exposure

Concerning the acoustic modelling of urban form, most aspects can be considered using available noise mapping software, including the background noise levels from a larger area. However, since these methods are not applicable to closed courtyards (Kropp et al. 2004), an extension is applied using results from the Qside project (Estevez Mauritz et al. 2014). A commercial software (Soundplan, version 8.0) is used following a prediction model (Nord2000 Road) that considers 27 frequency components of the sound (third-octave bands from 25 Hz to 10 kHz), five reflections and neutral weather conditions. The traffic flow on each of the local roads is 1500 vehicles/24 h (average for one year), consisting of 95 % light, 2.5 % medium heavy and 2.5 % heavy vehicles, driving 50 km/h. To estimate the non-direct noise exposure in the shielded yards, the input to the Qside model is given by the commercial software applied to the same case in terms of the road network but without the buildings and with hard ground. Further details are given in (Forssén et al. 219).

The comparison of the effects of the different morphological types will be made using mean and largest values of noise exposure (in dBA) as well as the standard deviation within the area. The values are taken from the street-block in the middle of the area studied (see Figure 3) to avoid disturbance from the context and ensure to isolate the impact of only building type on noise level distributions. The results will be presented for the yard (private land) and sidewalks surrounding the street-block (public land) separately. Further, maps of the whole area are used to discuss the distribution of the noise exposure.

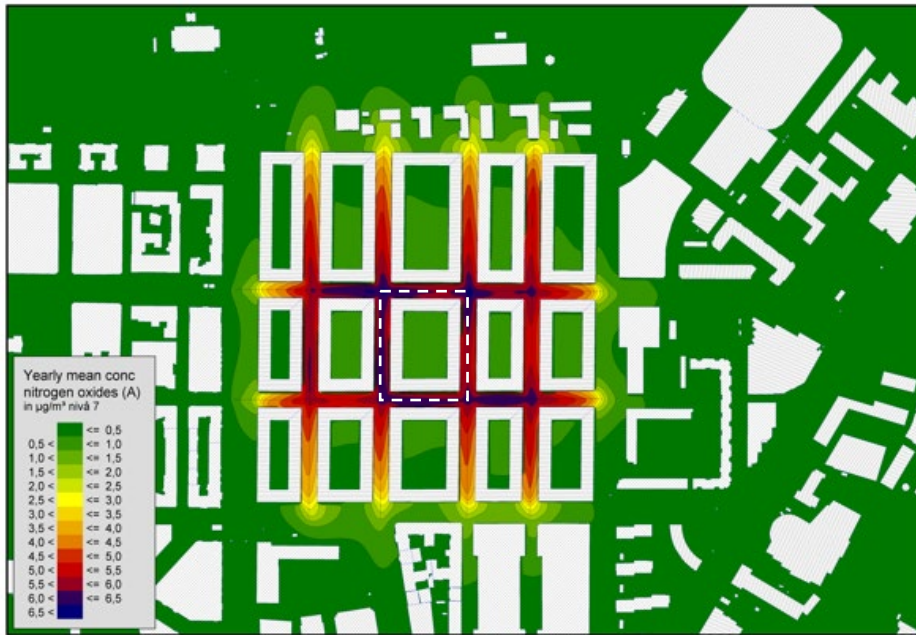


Figure 3. Distribution of yearly mean concentration of nitrogen oxides in model 11 where the middle street-block will be used for comparison of noise exposure and air pollution.

Modeling air pollution

For studying the effect on air quality of different morphological types, we use, for local modelling, the CFD-model (MISKAM) (Haeger-Eugensson et al. 2013). The meteorological input will be based on results from urban scale modelling (TAPM meteorological dynamic model (Chen et al.)), including the six morphological types that create a modified wind field. The comparison of the effects of the different types will be done using mean values (NOx values per unit area) as well as maps showing the distribution of the air pollutants in space. The results will be presented for the yard (private land) and sidewalks surrounding the street-block (public land) separately.

Results

For noise exposure, the results show that the mean values are relatively stable in the sidewalk area, while they increase in the yards, from 45 dB in case 11 (perimeter block type) to almost 55 dB in case 16 (point building type) (Table 2, Figure 4 & 5). The highest values in the yards reach almost 60 dB in case 16. Further, the values in the sidewalk and yard areas vary, depending on the morphological type, especially in the yards. Most variation in the yard is found in type 12 (U-block) and 13 (open corners), while type 11 (block) and 14 (strip) have least variation. Low mean noise exposure in type 11 is thus constant for the whole yard, while in type 12 and 13, we find areas with low, but also relatively high exposure. The yard in type 14 has less variation, but in general a higher exposure. Summarizing, the sidewalks are equally exposed to noise, independent of the morphological type, while the yards in the block type (case 11) perform much better than the strip (14), L-block (15) and point type (16). The half open block types (case 13 and 14) have lower mean exposure with relatively high variations. Typically, the open corners are more exposed to noise than the enclosed parts of the yard.

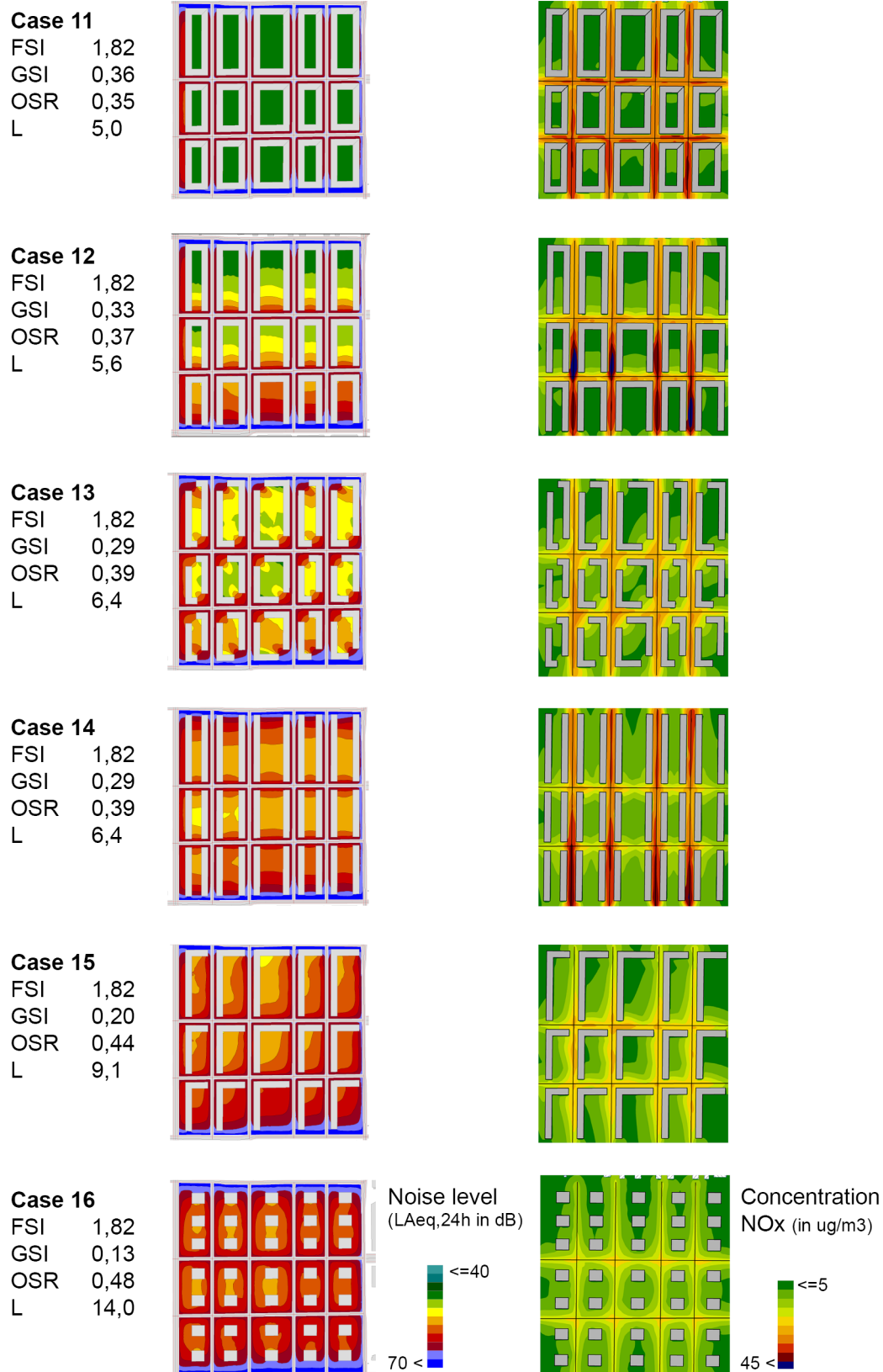


Figure 4. Distribution of noise exposure (dB) and air pollutants (NOx).

ID	Type	Noise exposure (dB)						Air pollutants (Nox)		
		Sidewalk			Yard			Sidewalk		Yard
		mean value	max value	standard deviation	mean value	max value	standard deviation	mean value	> 30 Nox	mean value
11	block	61,5	63,4	0,5	45,5	45,5	0,0	27,5	74%	8,3
12	U-block	61,0	63,2	0,9	50,0	54,4	1,8	29,3	50%	10,2
13	open corners	61,0	63,1	0,6	48,1	56,5	1,9	23,7	2%	9,2
14	strip	60,8	63,2	1,0	53,5	55,3	0,7	24,9	45%	8,5
15	L-block	60,4	63,0	0,8	53,8	56,9	1,1	21,1	0%	8,2
16	point	59,9	62,6	0,8	54,9	57,2	1,1	16,3	0%	10,5

mean and max values measured
in LAeq,24h (dB)

mean values measured in Nox;
max values (> 30 Nox) in % area
(sidewalk or yard)

Table 2. Mean values for the (private) yard area sidewalk area for the six models.

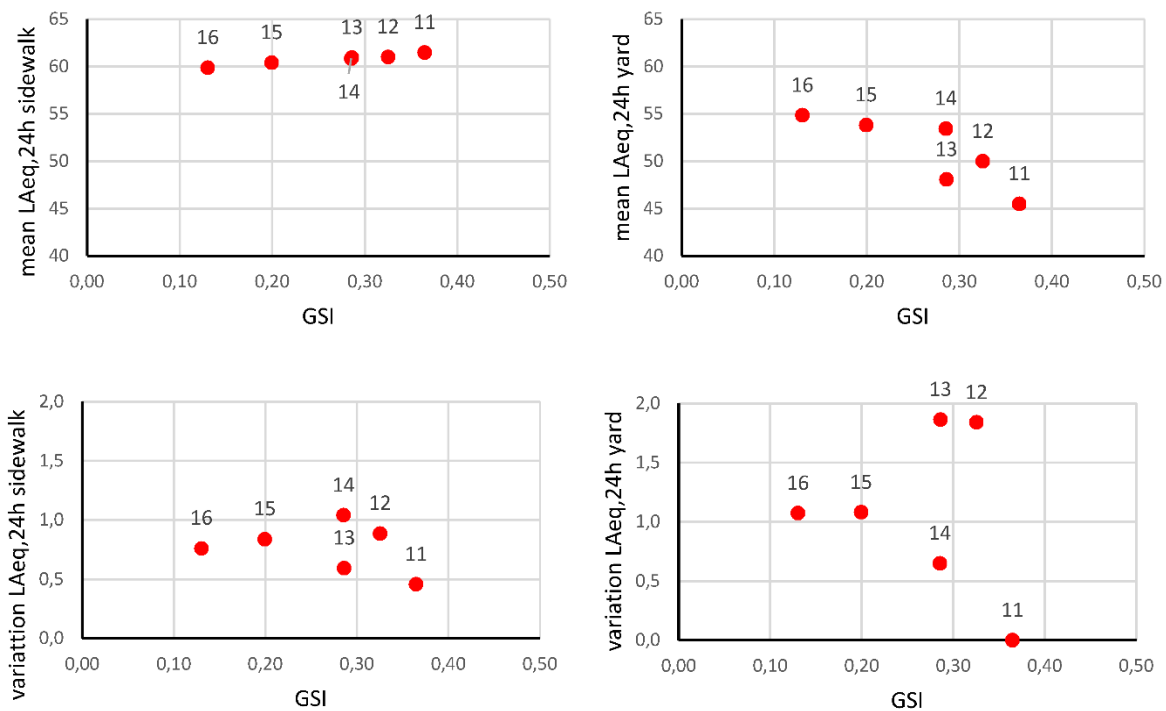


Figure 5. Levels of noise exposure (dB) in relation to building type and density (GSI values).

For air pollution, the results show that the mean concentration of nitrogen oxides are relatively stable in the yard area, while they increase on the sidewalks, from a yearly mean concentration of nitrogen oxides of 15 in case 16 (point type) to almost 30 in case 11 (block type) and 12 (U-block type) (Table 2, Figure 4 & 6). Furthermore, a high percentage of the sidewalks in case 11, 12 and 14 have a concentration of more than 30, while case 13 (open corners) stays below this threshold, despite similar mean levels.

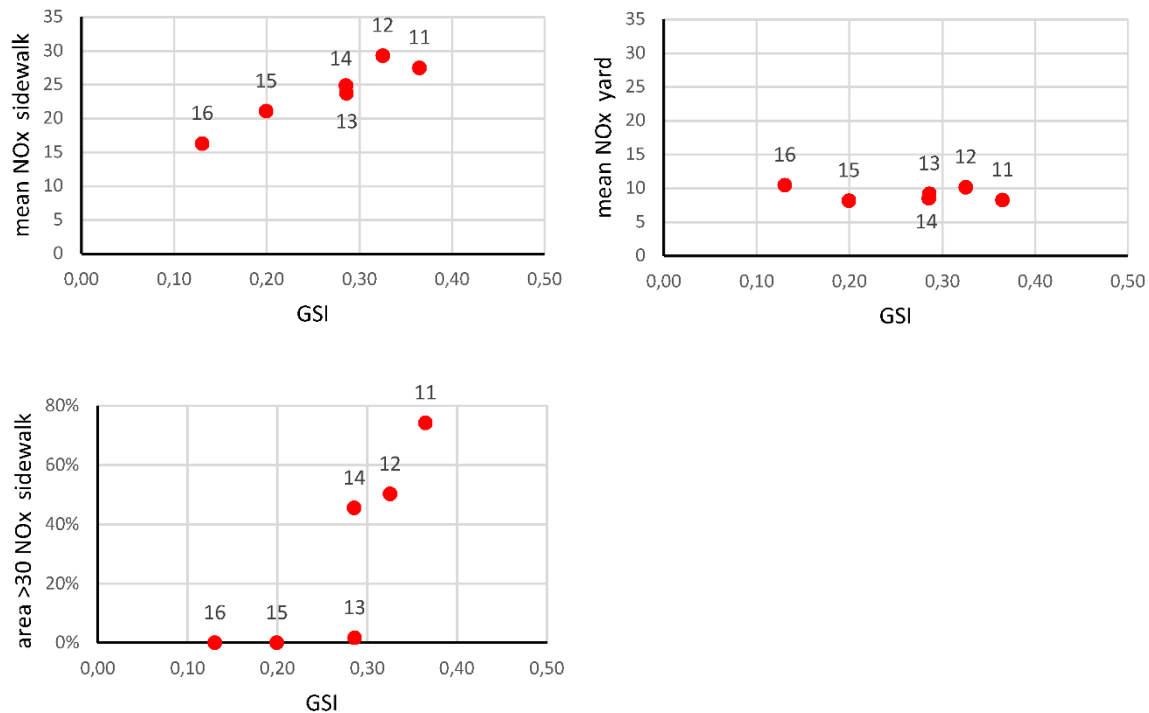


Figure 6. Levels of air pollutants (NOx) in relation to building type and density (GSI values).

Interestingly, the results of noise exposure and air pollutants show opposing results. Types that reduce noise exposure in the yards, increase air pollution on the sidewalks and vice versa, types that reduce concentration of nitrogen oxides on the sidewalk, increase noise exposure in the yards. This is most apparent for the block type (case 11) with “quiet yards, but polluted streets”, but also for the strip and point types (case 15 and 16) with “noise yards, but less polluted streets”. The other three types show a more complex tradeoff between noise exposure and air pollution: U-block type (12), open corner block type (13) and L-block type (14). From air pollution perspective, the open corner block type (13) performs better than the other two, because it has a more even distribution of pollutants on the sidewalks, while the others have similar mean values, but higher values on half of the sidewalk area. From the noise exposure perspective, the U-block type (12) and open corner block type (13) perform equally well with lower mean values and a high variation, meaning that the yards have, besides noisy areas, also more quiet parts. Thus, type 13 stands out positively in both perspectives, albeit not best from one perspective alone.

Conclusion and discussion

From the results discussed above, we can conclude that it is important to include multiple perspectives when discussing the performances of different urban forms. What seems to be optimal in one perspective such as noise exposure, is not necessarily doing well from another perspective such as air pollution. Calculating the combined health effect of both air and noise pollution would therefore be an important next step to seriously address these tradeoffs. For this purpose, we aim to use DALYs as used by the World Health Organisation (WHO). DALYs for a disease or health condition are calculated as the sum of the years of life lost (YLL) due to premature mortality in the population and the years lost due to disability (YLD) for people

living with the health condition or its consequences. By calculating this for the results of air and noise pollution as explained above, we can measure the combined health effects and the role urban form can play in reducing negative effects through the placement and form of buildings.

But already now, we can conclude that the half open block types and especially, the open corner block type (case 13) seem to combine these two perspectives well. The exact positioning of the openings in the blocks is something that needs to be studied more, as well as the impact of street width and variations in building height that has been argued to positively affect the distribution of the air pollutants in space. Furthermore, it is hypothesized that green facades could contribute to noise reduction that would be interesting to study in relation to the open block types discussed in this paper. Besides reducing air pollution, this could also contribute to the other ecosystem services such as biodiversity and pollination.

From the perspective of density, all cases presented and studied in this paper have the same FSI. However, the block type realizes this density with buildings of five floors, while the point type building needs 14 floors to arrive at the same FSI. While the first typology is very common in cities, the latter is built less often. When this type is found, it is often with less floors and thus a lower density. This is important for other aspects of sustainable urban development such as decreasing dependency of private cars in higher density solutions and thus reduces CO₂ and NO_x emissions and noise production. Furthermore, we do not know how building heights will affect noise exposure and air pollutants. This will therefore be studied in the next step of the research project MaGNA^{iv} which also this paper is the result of.

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ⁱ The Spacemate diagram refers to one of the projections of the Spacematrix diagram where three key variables are combined in a three-dimensional plot. See for more detail [Berghauser Pont and Haupt, 2010].

ⁱⁱ In the research project where this is part of other cases will be tested, such as the six types with constant number of floors and thus, varying FSI values; variations in street width; variations in building height within the same model.

ⁱⁱⁱ A comparable term for FSI, first used in New York City's Zoning ordinance in 1940, is the Floor to Area Ratio, FAR (Noble, et al., 1993).

^{iv} Morphology and Greening for Noise and Air quality. Increase the city's capacity by dealing with noise and air pollution through urban morphology and greening. Project leader is Jens Forssén, Technical acoustics, Chalmers. Other involved researchers are Laura Estévez Mauriz, Technical acoustics, Chalmers; Marie Haeger-Eugensson, COWI; Meta Berghauser Pont, Urban Planning and Design, Chalmers; and representatives of Gothenburg city. The project is funded by Formas.